AMBIENT WATER AND SEDIMENT QUALITY OF GALVESTON BAY:

PRESENT STATUS AND HISTORICAL TRENDS

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EXECUTIVE SUMMARY

For many years, data relating to the quality of water and sediment have been collected in the Galveston Bay system by a variety of organizations and individuals. The objectives of data collection have been equally varied, including the movement and properties of water, the biology of the bay, waste discharges and their impacts, navigation, geology, coastal processes, and fisheries. While the specific purposes of the individual data collection projects have limited each project in time and space, the data have great potential value to the Galveston Bay National Estuary Program (GBNEP) if they can be combined into a comprehensive data base yielding a historical depiction of the quality of the bay environment.

The purpose of this project was to compile and evaluate these data, and to employ these data in a quantitative assessment of water and sediment quality of Galveston Bay and its evolution over time. There were three key objectives:

(1) compilation of a comprehensive data base in machine-manipulable format;

(2) analysis of space and time variation (i.e, "trends") in quality parameters, i.e. characterization of the water and sediment quality of Galveston Bay;

(3) identification of probable causal mechanisms to explicate the observed variations.

Securing these objectives provides a foundation for further scientific study of Galveston Bay, and for a general understanding of the controls and responses of Bay water quality, which must underlie rational management of the resources of the system.

This study focused on the following categories of parameters:

temperature,
salinity and related parameters,
suspended sediments and turbidity,

pH,
dissolved oxygen,
nutrients, *viz.* nitrogen, phosphorus and organic carbon,
organics as measured by oil & grease, volatile solids and biochemical oxygen demand,
chlorophyll-a,
coliforms,
metals (total and dissolved), and
trace organics, including pesticides, herbicides, PAH's, PCB's, and priority pollutants

The requirements of the NEP Work Statement is that status-and-trends analyses be carried out for each of the Texas Water Commission Water Quality Segments presently in use in the Galveston Bay system. However, to secure the objectives of this project, it was necessary to perform analyses on a finer spatial scale than possible with the TWC segments. Therefore, a system of "Hydrographic Segmentation" was devised for Galveston Bay to form the basis for detailed analysis. This analytical segmentation was based upon present knowledge of the bay and rational physical criteria. Aggregation of data was based upon the determination of regions of homogeneity (within some statistical threshold), and zones or loci of sharp gradients in properties. The former corresponded to the interior regions of segments and the latter to boundaries between segments. This delineation takes into account transports, bathymetry, waste sources (where appropriate), inflows, and in general the distribution of physicochemical features which will either homogenize the parameter (to define the region encompassed by a water quality segment) or create steep gradients (to define the boundary between segments). The differences between the TWC and hydrographic segmentations are:

(1) The TWC segments tend to be larger in space, especially within the open bay, and generally have arbitrary or political boundaries;

(2) The hydrographic segments are smaller in spatial extent and are defined by principal geomorphic controls on flow and/or known predominant flow patterns;

(3) The TWC segments include tributaries of the principal inflows but exclude the Gulf of Mexico;

(4) The hydrographic segments focus upon the bay system *per se*, its immediate periphery, and the nearshore Gulf of Mexico, but do not consider the upper reaches of the tributaries.

All statistical analyses were performed for *both* segmentations. Any partitioning of the data in space or time involves trade-offs in statistical confidence. The more segments that are defined (i.e., the smaller their spatial extent), the fewer data points that will be placed in each segment. While spatial variability is better delineated, the statistical confidence in the values at each segment is reduced because of the fewer number of data points. On the other hand, to improve the number of data points by aggregating into larger segments is to introduce more "noise" in the data due to spatial variability; the ultimate extreme of this strategy is a baywide analysis, in which all available data are used to compute the statistics, but the high variance renders the computed statistics practically useless. The hydrographic segmentation developed in this study, in which the bay system and periphery are subdivided into 141 segments, represents our best compromise between a sufficient data record in each segment for meaningful analyses and a sufficiently small and well-defined segment domain so as to reduce the spatially-induced noise.

Formal relationships between various quality parameters were given detailed consideration, for two purposes. First, from an analytical viewpoint, the used of one parameter may have conceptual advantages over another, e.g. DO deficit may be more indicative of oxygen conditions than the concentration of dissolved oxygen itself. Second, while related parameters are technically distinct, the fact that they can be associated and may be converted from one to another means that a much denser and longer-duration data set can be compiled by converting these to a common parameter. These are referred to as "proxy" relationships, and their derivation and justification was a central step in the Galveston Bay trend analysis. Proxy relationships were employed relating salinity to conductivity, density, and chlorinity, total suspended solids to Secchi depth and turbidity, five-day biochemical oxygen demand (BOD) to other durations and nitrification-suppressed BOD's, and DDT to concentrations of the primary isomer. Proxy relations were sought but rejected for fecal and total coliforms, the various species of nitrogen, and different measures of phosphorus. Dissolved oxygen was analyzed both as total concentration and as deficit below saturation, the latter removing temperature and salinity dependence upon solubility therefore better exhibiting the DO "climate" stripped of its seasonal variation. Coliforms were treated both as raw concentrations and log-transformed concentrations.

Historical and current data collection programs in Galveston Bay were reviewed. We differentiate between monitoring, survey and research programs. Monitoring programs are put in place for a protracted or indefinite period for the purposes of sampling a suite of variables, and are usually multi-objective. A key characteristic of a monitoring program is consistency in the suite of variables acquired, since it is the accumulation of a long-period data base that is the purpose of the program. Important monitoring programs currently operating in Galveston Bay are the Texas Water Commission Statewide Monitoring Network (SMN) sampling, the Texas Parks and Wildlife Coastal Fisheries Program, and the Texas Department of Health Shellfish Sanitation Program. A survey, in contrast, is characterized by a definite limit in time. It may be a one-time sampling run, or may be a few such runs carried out within a relatively short calendar period. A survey is usually multi-objective and emphasizes spatial distribution of a suite of parameters at a point in time. Examples are the Submerged Lands Project of the University of Texas Bureau of Economic Geology, sponsored by the Texas General Land Office, and the survey programs of the Texas Water Development Board Bays and Estuaries Program. Finally, a research program is formulated to address a specific hypothesis, that in turn dictates the suite of measurements. These three general strategies of sampling overlap in practice: many monitoring programs provide data for research, many research programs comprise monitoring, and either can contain surveys as a part of the program.

Of the historical programs on Galveston Bay, most important is the Galveston Bay Project (GBP), a comprehensive study of the system conducted by the Texas Water Quality Board, which involved monthly sampling at a network of fixed stations for the period 1968-72, as well as numerous research programs. One of the important accomplishments of the GBNEP is the recovery of the digital data file from this signal program, a data file that had been lost for years. Another noteworthy program is the Submerged Lands Study of BEG, which focused entirely upon sediment, and is the only data set extant which samples the entirety of Galveston Bay at a uniform station distribution. In the past, the Texas State Department of Health analyzed a broader suite of parameters and more widely distributed sampling stations than is the case for the current program. Especially for the period 1963-67, TSDH carried out intensive sampling throughout the system. Even earlier, the TSDH in cooperation with local and county agencies performed sampling of coliforms, salinity, temperature, BOD and pH in the system, providing data records back to the early 1950's. In the period 1958-1967 the U.S. Bureau of Commercial Fisheries undertook an extended and intensive sampling of the Galveston Bay system, primarily directed at biological sampling, but also including hydrographic and water quality data. This was one of the most intensive continuous, consistent hydrographic surveys ever performed on the Galveston Bay system as a whole, and was also the first to employ large-scale digital data manipulation as an intrinsic part of the program. The digital record from this project has been lost for years.

This Status and Trends project compiled data from 26 separate data collection programs, including all of those listed above as well as the Galveston District U.S. Corps of Engineers (USCE) O&M water and sediment surveys, the USCE 1970's survey of the Trinity delta, and numerous academic research studies. This project benefited from the recovery of lost major data sets accomplished in the preceding GBNEP Data Inventory project (Ward and Armstrong, 1991), including the Galveston Bay Project (noted above) and about half of the digital record of the above-noted USBCF hydrographic program. The SMN, TSDH shellfish sanitation water-quality data, the hydrographic data of TPWD, and the coastal data file of TWDB were obtained in digital form from the respective agencies. The other data sets were keyboarded as a part of this project.

One of the principles observed in the construction of the Galveston Bay data base was the maintenance of integrity of the individual surveys. While the various data sources were later combined in various ways as a part of different analyses, it is mandatory that the data compilation be capable of separating and identifying, data from various agencies, as they may differ in accuracy, methodology and procedure, differences which could become crucial in interpreting apparent trends or in more specialized analyses. Therefore, in the compilation of data for a given parameter, the coded information included identification of the data source, and was input without any modification, including retention of the original units of measurements. This is one aspect of differentiating the *source* data base from *derivative* data bases. The source data base codifies the original measurements as reported by the originating agency. This data base therefore contains exactly the information in the original: nothing is lost or added. (Even an apparently innocuous conversion of measurement units can introduce a distortion.) For various analytical purposes, these data must be modified, for instance converted to common units, averaged in the vertical, aggregated, or screened out according to some criterion. The data set so processed is a *derivative* data base. Any number of derivative data bases can be created according to the needs of a scientific investigation. It is our opinion, however, that the source data base, once established, should remain inviolate and sacrosanct. Thus the basic approach in this project was to first create the source data base for a given parameter through the data compilation effort. Then various derivative bases were formed to selectively include certain subsets of the data and to subject these to specific processing.

In order to be able to process the data spatially, the sampling points in space must be expressed quantitatively. In this project, latitude/longitude coordinates were used to locate the horizontal position of the sample, and depth (i.e., distance below the water surface) to locate the vertical position. The former required precisely plotting the sampling stations from descriptions or from project maps and determining by manual measurement the coordinate positions, which were then keyboarded into a digital data base. Much of this effort had already been carried out for the Data Inventory Project (Ward and Armstrong, 1991), but the new data sets located during this work required station positioning and digitization.

With each measurement in this data compilation there is included an estimate of its uncertainty. This is important because data bases are created by the combination of data sets from different sources, with differing analytical methodologies, different agency objectives, and differences in field procedures. In this project, we define the uncertainty as the magnitude of the population standard deviation about a fixed value of the variate. For practical purposes, we usually estimate this by the standard deviation about the mean of the measurements under idealized conditions. This was evaluated in several ways depending upon the extent of documentation for the data set, in decreasing order of preference:

(a) review of QA/QC procedures observed by the collecting agency, as reflected in practices memos, manuals and directives;

(b) identification of the specific methodologies used and their established accuracy;

(c) statistical variation of the measurements themselves, relative to some external standard, e.g. a more accurate proxy relation or data from a contemporary, independent source;

(d) judgement, based upon experience with the method or equipment, and upon the practice of workers in the field using that methodology.

With this uncertainty so quantified, a data user has the basic information necessary to retain or reject the data, and to further determine how the uncertainty is affected by whatever processing the data may be subject to, e.g., aggregation, units and proxy transformations, and averaging.

Because the NEP primary data bases were compiled from various original data sources, some digitally and some manually, there is the possibility of error. Therefore, specific QA/QC measures were introduced to minimize the occurrence of error, and maximize its detection, including keyboard formats which mimic the source hard copy, manual spot checking versus the original source, and post-entry data screening, i.e. testing for values within "reasonable" bounds, spatial continuity (as reflected by simultaneous data from different depths or nearby stations) and temporal continuity (comparison with measurements at the same station before and after the sampling time). The errors introduced by the data transfer procedures of this project were the simplest to deal with, because their existence (i.e., that they were in fact errors of entry) could be confirmed by comparison with the original source, and corrections could be expediently implemented. The same screening process also detected aberrant values in the source data files themselves. When possible, we contacted the agency source to verify or correct the reported information. For most of the data files, however, there is no longer an authoritative source with which to compare the reported data: the original field sheets are discarded, or the principal investigator or originating agency is not accessible (or even extant). This forced us to make probability judgements. Consonant with our philosophy of leaving the source data files sacrosanct, "corrections" were introduced into these data files only when the typographical error was "patently obvious."

The principal steps in data-processing in this study were:

(1) For each historical data program in the Galveston Bay system, compile a Primary Data File, consisting of the digital record of measurements, supplemented by latitude/longitude coordinates and uncertainty;

(2) For each parameter of concern, sift through the Primary Data Files, applying whatever screening, proxy relationships, and units conversions are necessary, to create a Master Derivative File for that parameter;

(3) Sort the Master Derivative Files into geographic segments for the Galveston Bay system;

(4) Perform specific statistical and trends analyses, including further averaging and data screening, as warranted.

We regard the Master Derivative Data files to be our principal data resource product from this study. These contain all of the data for each parameter that we were able to locate and digitize, and incorporate our judgment on which data should be retained or rejected. They are coded in a uniform ASCII format for ease of dissemination and use by other researchers. Generally, as a matter of personal philosophy, we rejected very little data in the formulation of the Derivative Files, and reserve further data screening for the specific analyses to which the Derivative Data Bases are subject. Data were rejected if the date, position, or depth were obviously impossible and there were no satisfactory means of judging the correct value. Generally, we did not reject data at this stage based on the parameter value, but reserved that for later steps in the analysis. All told, the digital compilation of 73 water-quality parameters and 50 sediment-quality parameters is the most extensive and detailed long-term record of water quality ever assembled for Galveston Bay. Each measurement record includes the date, sample depth, latitude and longitude of the sample station, measured variable, estimated uncertainty of measurement expressed as a standard deviation, and a project code identifying the origin of the data.

The derivative files were used to examine the general magnitudes and spatial distribution of water and sediment quality parameters in Galveston Bay. Time trend analysis was approached by a linear regression of the measurements versus time. From the environmental-quality analysis viewpoint, the most important regression parameter is the slope. This is the average (in the least-squares sense) rate of increase (if positive) or decrease (if negative) in the magnitude of the water quality variate, in units of the variate per year. It is the key indicator of a systematic change in that water-quality variate.

For many of the variates, measurements are occasionally—or frequently—below detection limits (BDL) of the methodology. These data records were treated in three different ways. First, the measurements BDL were ignored, as providing essentially no quantitative information. Second, the BDL values were replaced with zero in the analyses, on the argument that for practical purposes the parameter is not present. Third, the BDL values were replaced with the value of the detection limit, on the argument that the potential concentration of the variate is the detection limit of the methodology. In our view, the choice is dependent upon the purpose at hand. The non-BDL statistics can provide some insight into the precision and variability of the parameter, which the more constant DL values would corrupt or even mask. However, to completely ignore BDL results is to lose information, albeit non-quantitative. The fact is that a water or sediment sample was obtained (usually at great effort), a careful analysis performed, and an upper bound established on the concentration of the parameter. This information should not be dismissed cavalierly. The latter two alternatives use that information, either optimistically or pessimistically, depending upon the intent of the analyst. Since all three alternatives were employed in our analyses, the user of these results therefore can choose among them to best suit his purpose.

Adequacy of a data base is relative to its ability to resolve the various scales of variation, and in this respect Galveston Bay is generally undersampled. Despite the hundreds of thousands of separate measurements compiled in this study, from extensive and overlapping routine monitoring and survey programs by several state agencies and numerous special surveys, when these data are subdivided by specific parameters, each of which measures a different aspect of the water quality "climate," aggregated by region of the bay (segments) and distributed over time, the data record is seen to be rather sparse. Continuity in space is undermined by too few stations, and by inconsistency in the suite of measurements at different stations. Continuity in time is undermined by infrequent sampling, and the replacement of one parameter by another without sufficient paired measurements to establish a relation. Past and present sampling practice does not permit analysis of time scales of variation shorter than a few days.

Ability to resolve long-term trends in the face of high intrinsic variability requires data over an extended period. The extant period of record for Galveston Bay, with adequate continuity for trends analysis, extends back only to about 1965, except for some traditional parameters and for certain areas of the bay, for which the record can be extended back to the late 1950's. As salinity and temperature are the most easily measured variables, they represent the densest and longest data record. For metals and for complex organics, the period of record may extend back only a decade or so. Many of these measurements are below detection limits. For sediment, the data base is even more limited, amounting to one sample per 5 square miles per year, and is much less for some metals and organic pollutants.

The principal external controls on bay quality are hydrography, hydrology, and loadings. Hydrographic factors include tides, meteorology, and density currents. Tides are the most direct effect of the sea, are maximal at the inlets to the system and decline in amplitude rather quickly into the interior of the bay, especially in traversing the inlets and the mid-bay constriction at Redfish Reef. The bay is most responsive to meteorological forcing, which is manifested as windwaves, internal circulations and wind setup and setdown. Windwaves contribute to the vertical near-homogeneity of the bay and its high mechanical aeration. Setup and setdown are the response of the water surface to changing wind regimes, especially dramatic during frontal passages, when as much as half of the volume of the bay can be evacuated through the inlets. Density currents are the primary mechanism for salinity intrusion, and are especially prominent in the deeper areas of the bay, notably the dredged channels.

The normal pattern of Trinity River flow is composed of an annual "flood" and an annual "drought." The flood is the spring freshet, and the drought is the summer low-flow season. There is, however, considerable interannual variability in the river flow. Some years exhibit a pronounced and extended freshet, while in others the spring freshet may be totally absent. The summer drought may be shortened or even eliminated by unusual runoff, or may be prolonged and the flows dwindle to nothing. The gauged flow of the Trinity was analyzed to quantify the time signal of hydrology. The 3-month "freshet," the first month of which is most commonly April and next January, was determined to comprise about *half* of the annual flow of the river, and to have an interannual spread of over two orders-of-magnitude in volume. A Fourier analysis of the 65-year time signal of freshet volume disclosed significant spectral peaks at 3.5-4 year and 13-14 year periodicities. The four-month (July-October) summer "drought" period comprises less than 15% of the annual discharge of the river, with strong spectral peaks at periodicities of about 5 and 7-8 years, as well as wider bands of 3.8-4.8 and 14-18 years in the Fourier analysis of the 65-year time signal. No statistically significant trend in total inflow volume over the period of record was detected.

The influx of conventional pollutants as a mass load from both point source discharges and inflows peaked in the 1960's and has declined since. One prominent reason is the implementation of advanced waste treatment. A 20-fold reduction in BOD loading has occurred since about 1970. The nitrogen load has declined as well, though not so greatly. Reductions in industrial nitrogen loads began to be implemented in the early 1970's, somewhat sooner than for municipal discharges, and the reductions probably are much greater proportionately than that of domestic discharges. At present, the industrial nitrogen load is estimated to be about one-third the domestic load. In addition there has been a decline in mass loading from the river and stream inflows due to a combination of improved waste treatment, altered land use, and impoundments on the principal rivers and the concomitant entrapment of fine-grain sediments. As many nutrients and contaminants are associated with these finer particulates, these reservoirs are therefore also considered to represent an effective sink of these constituents in the inflows. Reliable data for estimating this effect are sparse, however. Following the closure of Livingston on the Trinity about 1970, both annual load and mean concentration of suspended sediments in the river downstream from the reservoir have fallen to one-third of their pre-lake level. There is a reduction in both the mean concentration and the variance of downstream nitrate concentration with Livingston on-line. A three-to-four-fold decrease in total nitrogen loading of the Trinity is estimated to be due to Livingston.

Salinity acts as a conservative property of Galveston Bay waters whose concentration is primarily determined by boundary fluxes at the inflow points and at the inlets to the sea, and internal transport and mixing. Many water quality parameters have a general spatial distribution directly or inversely homologous to salinity, either decreasing or increasing from points of inflow into the lower bay and to the inlets. Because the inflow regions are also generally the foci for loadings of solids, contaminants and nutrients, there is a similar distribution in many of these variates.

Substantial gradients across the bay are a normal feature of salinity structure, declining on average from values about 30 ppt at the inlets to the bay to about 3 ppt out from the principal points of inflow, such as the Trinity River. Variability about these mean values is high, however, with a standard deviation of 5-6 ppt throughout the bay. Salinities in the open-bay reach of the Houston Ship Channel are higher, on the order of 2 ppt, than those of the adjacent waters. Vertical stratification of bay waters is slight, by estuarine standards, generally averaging less than 0.6 ppt/m, and averaging less than 0.3 ppt/m over about half of the bay area, with no correlation with water depth.

While freshwater inflow is the ultimate control on salinity, inflow proves to be a poor statistical predictor of salinity, achieving only about 50% explained variance in the data even with long-term processing of the inflow. Improved salinity prediction will require more sophisticated accommodation of the time-response dependency of salinity on inflow and other internal transports operating in the system.

There has been a general decline in salinity over the three-decade period of record, of about 0.1-0.2 ppt per year, not clearly associated with freshwater inflow. Our favored hypotheses (whose testing exceeded the scope of this study) are variations in the time signal of inflow events and the associated salinity response, reduced salinities in the adjacent Gulf of Mexico, or reduced intensity of interaction between estuary and Gulf waters.

The parameter pH is rather uniform, with its higher values, on the order of 8, in the more saline regions of the bay, an expression of the high buffering capacity of sea water.

Temperature in Galveston Bay is primarily controlled by surface fluxes, especially the seasonal heat budget, and much less—if at all—by boundary fluxes and internal transports. The horizontal gradient across the bay ranges 1-2°C, with the higher values in winter, with little systematic stratification, though on average a slight stratification on the order of 0.2°C/m emerges from the data. We believe this stratification to be due to near-surface heat absorption, rather than density effects. The seasonal signal is, of course, the principal source of variation in water temperature. Over the three-decade period of record, water temperature, especially in the summer, has declined in Galveston Bay at a nominal rate of 0.05°C/yr. Our favored hypothesis for this decline is an alteration in climate (e.g., air temperature, wind, cloud cover), though this could not be tested within the scope of this project.

Dissolved oxygen is generally high throughout Galveston Bay, averaging near saturation through large areas of the bay, with frequent occurrence in the data record of supersaturation. Exceptions to this are in poorly flushed tributaries subjected to inflow and waste discharges, most notorious of which is the Houston Ship Channel. These near-saturated conditions are a manifestation of the intense vertical mixing processes in Galveston Bay, which produce mechanical surface aeration, as well as a manifestation of photosynthetic productivity. In the open, well-aerated areas of the bay, vertical stratification is on the order of 0.4 ppm/m. This stratification is much greater than the practically negligible stratification in solubility (due to the weak stratification in temperature and salinity), and is considered to be the result of DO influx near the surface in concert with water-column and sediment biochemical oxygen consumption.

In Galveston Bay, BOD ranges 2-3 ppm throughout the lower bay segments, and increases inland to 4-5 ppm in the upper bay along the north and west shores, and to values greater than 5 ppm in Clear Lake and the Houston Ship Channel. Substantial reductions in waste loads into Galveston Bay have been implemented in the last two decades. In the Houston Ship Channel, which receives the bulk of waste discharges in the system, the reduction in loading has been remarkable: a factor of 20 reduction in BOD loading since 1970. Within the upper HSC, the reach above the San Jacinto confluence, the DO deficit has been reduced about 4 ppm in the past 20 years.

Like all of the Texas bays, Galveston is turbid, with long-term average total suspended solids (TSS) ranging 30-40 ppm throughout most of the bay, somewhat higher in the upper bay (above Redfish Reef) and less in the lower bay, and 40-60 ppm within the tributaries and adjacent open-water segments. Stratification in TSS is noisy, but on the order of 5 ppm/m declining upward, which is consistent with settling of larger particles to the bottom as well as a near-bottom source of particulates from scour of the bed sediments.

The remarkable feature of TSS in Galveston Bay is its decline throughout the system: over the past three decades, an average reduction of about 2 ppm/yr to current levels on the order of 20 ppm (averaged over the period since 1988). We favor the hypothesis of a general reduction of TSS loading to the bay (in contrast to one of decreased sources within the bay itself,.e.g., resuspension), due to one or a combination of TSS reduction by advanced waste treatment, TSS entrapment within reservoirs, and reduced TSS in runoff because of changing land use. The relative importance of these could not be tested within the scope of this study, since it would require detailed mass-budgeting. However, we note a reduction in Trinity River TSS (both load and concentration) by a factor of three since the closure of Livingston in 1970, and we estimate an order-of-magnitude reduction in TSS load from waste discharges, similar to the reduction in BOD loading.

Nitrogen and phosphorus nutrients in Galveston Bay exhibit the same general spatial distributions as BOD and TSS, *viz.* elevated concentrations in tributaries and regions adjacent to inflow points, declining to lower concentrations at the inlets. Because these nutrients have an affinity for fine-grain particulates, their association with TSS is more than coincidental. The levels of concentration of total inorganic nitrogen range up to about 0.2 ppm in the lower bay (below the mid-bay constriction at Redfish Reef), 0.2-0.5 ppm in the upper bay, and as much as an order of magnitude greater in the upper Houston Ship Channel.

These nutrients, as well as total organic carbon, all exhibit declines in concentration throughout the bay over the past two decades, total ammonia N on the order of 0.1 ppm/yr, total nitrate on the order of 0.01 ppm/yr and total phosphorus on the order of 0.05 ppm/yr. We favor the hypothesis that these reductions in nitrogen and phosphorus are a consequence of decreased wasteloads from advanced waste treatment and decreased loadings in the inflows, perhaps due to reservoir entrapment or altered land uses. (Nitrate exhibits increasing trends in the tributaries, which is almost certainly a result of increased nitrification due to advanced waste treatment. However, the net inorganic nitrogen load is decreasing.)

Total organic carbon since 1988 has averaged about 3-5 ppm in the open bay and about 8 ppm in the Houston Ship Channel. As noted above, total organic carbon exhibits baywide declining trends similar to nitrogen and phosphorus, except in West Bay (where there is no discernible trend), on the order of 0.5 ppm/yr. The recent levels given above are about one-third of the concentrations of the mid-1970's. This decline could be a direct result of reduced carbon loading, or an indirect effect of the general decline in nutrients on decreased productivity. Some credence is given the latter possibility by the decreases in chlorophyll-a in the open bay, to levels about one-half of those a decade ago.

Contaminants such as oil & grease, coliforms, metals and trace organics (pesticides, PCB's) show elevated levels in regions of runoff and waste discharge, with generally the highest values in the upper Houston Ship Channel, and generally low values in the open bay waters. Most of the metals are declining in areas of maximal concentrations. While this may well be an artifact of changing analytical techniques, we favor the hypothesis that this general decline in metals is closely related to the decline in suspended solids. Most measurements of trace organics such as pesticides and priority pollutants are below detection limits, so we have no statistically reliable information on trends.

The conventional organic measures and metals in Galveston Bay sediments appear to follow the same general spatial distribution as most of the water quality parameters, *viz.* elevated concentrations in regions of runoff, inflow and waste discharges, and lower, more-or-less uniform concentrations in the open bay, with the Houston Ship Channel generally the focus of maximal concentrations in the system. The available data for conventional organic measures are sparse, with large areas of the bay unsampled, and generally too noisy for reliable detection of trends. A glaring deficiency is the almost total lack of paired chemical and texture analyses. Without basic grain-size information, it is impossible to sort out much of the variability in sediment quality.

Where trends in the sparse, noisy data for sediment metals are statistically discernible, they tend to be declining, especially in the upper Houston Ship Channel. In the Channel, the rates of decline in sediment concentration per decade are for chromium, mercury and zinc a factor of two, for copper and nickel a factor of three, and for arsenic, cadmium and lead an order of magnitude.

These data were examined for indications of problem areas. In summary, the geographical problem areas of Galveston Bay hold no real surprises; they are where we expect them to be: in regions of intense human activity, including urban areas, points of surface runoff, waste discharges, and shipping. The analyses of this study yield a quantification of the water and sediment quality in these problem areas. Perhaps unexpectedly, the quality of the bay is generally good, and where it is degraded there is a trend of improvement, in many cases substantial. The greatest problem of concern to these investigators is the systematic decline in nutrients, suspended solids and chlorophyll. No quantitative information exists defining an "optimal" level of nitrogen and phosphorus in Galveston Bay. Earlier studies during the Galveston Bay Project determined that nitrogen was probably the limiting nutrient in Galveston Bay, in which case its decline on the order indicated in this analysis would result in a decreased productivity of the bay.

Recommendations deriving from this project fall into two categories: data collection and additional studies. With respect to data collection, we re-emphasize the observation that Galveston Bay is inadequately sampled with respect to almost all variables examined in this project. Few programs can afford the investment of long-term, comprehensive, intensive data collection in a system such as Galveston Bay. To address scientific and management questions that require such massive data bases, we must depend upon the use of data collected by different agencies for perhaps different purposes. In this sense, data collection should be regarded as a collective enterprise, and its design should reflect a certain degree of scientific altruism, to ensure maximal utility of the data without undermining the principal purpose of the data collection activity. Specific recommendations include the following:

(1) A greater sensitivity is recommended to the investment in putting a sampling crew (and usually a boat) on a specific station. The incremental cost (including loss of efficiency) in acquiring additional measurements, perhaps peripheral to the principal objective of the sampling, must be weighed against the much larger cost of occupying the station, in specifying the suite of parameters to be obtained. When the major investment of time and expense is to place a boat crew on station, a few *in situ* measurements should be standard procedure. If the crew is equipped with electrometric over-the-side probes, a vertical profile instead of a single depth should be routine. Some limited water sampling may also be easily accommodated, perhaps just surface grab samples for straightforward lab analyses. Much greater benefit could be derived from the public investment in the various state sampling programs if this principle were observed. We suggest that short lists be formulated of "recommended" parameters, to be included within suites of measurements of various classes (e.g, *in situ* parameters, non-fixed water samples, sediment sampling for chemical analysis, etc.), to provide guidance to anyone undertaking a sampling project, including research projects.

(2) The same principle of incremental cost versus benefits should be considered in specifying laboratory analyses. Many procedures, e.g. mass spectrometry or grain-size by settling tube, are cost-loaded in sample preparation, and can admit additional parameters or greater resolution with minor incremental cost.

(3) Necessity for both continuity in time and continuity in space must be recognized, as well as the need for maintenance of a long period of sampling. There are numerous examples in the data record when a parameter is suspended from further measurement. In most cases, this has involved a replacement of the old parameter with a new one. When a new, more accurate parameter is considered to replace another, there should be a continuation of data for the older variable together with the new parameters to at least establish an empirical relation. It may be more important to continue the measurement of the older parameter, to preserve the continuity of record, even if the utility of that parameter is limited relative to more modern techniques.

(4) We note that the intratidal-diurnal scale of variability is virtually unsampled in Galveston Bay, yet there are several parameters, such as dissolved oxygen, temperature and salinity, with significant variation on these scales. The use of electrometric sensing and automatic data logging now permit the recovery of nearly continuous, fine-scale time signals of several of these parameters, and should be incorporated into routine monitoring of the bay, perhaps in association with tide gauging. Such data acquisition should not replace routine sampling, since routine sampling provides far better spatial continuity than is practical to achieve with automatic monitors.

(5) A great deal of information loss presently occurs due to incomplete field notes, laboratory analysis and transcription errors, and data entry errors. Field notation should always be made of conditions, sampling location, and time and date. (This is frequently not done.) This information should be included in later data entry. Any data collection program should include procedures of *timely* data screening and data-entry verification, from the original lab sheets to the digital data file. From an economic viewpoint, the expense of data checking shrinks to negligibility compared to the unit cost of acquiring and analyzing a water sample. One can not afford to lose that considerable investment because of an errant keystroke or a myopic view of the need for data checking. The error rate in the TWC SMN is surprisingly high, considering the central importance of this data base to water management in Texas. Again, it may be useful for GBNEP to develop a standard list of data recording and verifying procedures as guidance.

(6) Data entry error is not the only means of losing information from data collection. Replacing a series of raw measurements over time or space by an average, failing to preserve information on sampling time, position or conditions, or intermixing actual measurements with "estimated" values without any means of separation, all represent losses of information. We recommend adherence to the same principle of preservation of data integrity observed in this project, in which the raw data is preserved as a separate record from its combination with other data or its further processing. Agencies should differentiate between the data record of observations obtained by that agency, and a compiled data record of those and other external measurements, possibly further processed. At present, several agencies, e.g. TWC and TWDB, intermix such data in a single data base.

(7) Some measure of suspended solids (e.g. turbidity) should be included in routine monitoring. For nutrients, metals, organic pesticides, PAH's or similar constituents that have an affinity for particulates, suspended solids *per se* should be routinely determined as part of the suite of measurements. Further, the analysis should include grain-size distribution or at least a simple filtration to determine partitioning of clays-and-finer and silts-and-finer.

(8) A ubiquitous deficiency of the sediment data base is that there are almost no paired measurements of chemistry and sediment texture (i.e., grain-size distribution). Analysis of the variability of many of the parameters of concern in environmental management, such as heavy metals and pesticides, must consider the grain-size fractions. We recommend that texture analysis be instituted as a routine aspect of any chemical analysis of a sediment sample.

(9) Because of the future potential rôle sediment organic carbon may play in evaluating sediment chemistry with respect to a standard, presuming the EPA Equilibrium Partitioning approach is adopted, we recommend that organic carbon be instituted as a routine aspect of any chemical analysis of sediment involving non-ionic organic contaminants, especially organohalogens. While it is premature to offer this as a recommendation, we draw attention to the possible rôle of acid volatile sulfide as a normalizing parameter for standards for metals in sediments, hence the desirability of instituting this parameter as a routine aspect of any chemical analysis of sediment involving heavy metals.

Recommendations addressing further analyses and studies are as follows:

(1) Detailed mass-budgeting studies are recommended to determine the probable cause of the apparent declines in particulates and nutrients, perhaps in concert with hydrographic analyses or deterministic models, using the data base compiled in this project. These should include detailed information on waste discharges and reservoir entrapment. Event-scenario analysis as well as time-series studies could both provide insight. This should be extended to include numerical modeling, as an "interpolator" in space and time.

(2) Additional analysis of chlorophyll-a and related measurements from Galveston Bay, in association with *in situ* productivity studies are needed. Some special-purpose data collection activities, such as the Intensive Surveys of the Texas Water Commission and the National Marine Fisheries Service might be profitably used in a more targeted analysis. These studies should include detailed examination of phytoplankton dynamics in Galveston Bay, and its dependence on water quality. Analysis of the time-response behavior of selected higher organisms might also be useful.

(3) Metals and trace organics remain a major concern. The present analysis was significantly circumscribed by the sparsity of data and the precision of measurement. Clearly, more and better measurements are necessary to assess and monitor this suite of variables. On the other hand, the investment in complex and demanding analyses does not at the moment seem highly critical to the management of Galveston Bay, apart from the present state and federal activity in wasteload regulation. While monitoring should continue, we do not believe that merely intensifying that monitoring will yield information in proportion to investment. We recommend a research focus on:

- (a) improved measurement methodology, including relations with and among older methods, for interpretation of historical data, and better determination of precision and accuracy,
- (b) bioaccumulation of metals and trace organics,
- (c) detailed studies on kinetics and fluxes in carefully selected regions of the bay subject to identifiable and quantifiable controls,
- (d) exploration of suitable tracers and their measurement, such as aluminum, to separate natural and anthropogenic sources of metals.

While information is needed on open-bay environments in general, the greater effort should be invested in those regions already manifesting a proclivity for elevated metals and pesticides, i.e. in regions of runoff, inflow, waste discharges and shipping.

(4) In an estuary as turbid as Galveston Bay, the rôle of sediments in suspension and in the bed is quintessential. Every element of the sediment transport process is imperfectly understood, as manifested in our inability for quantification, from riverine loads to exchange with the Gulf, from scour and deposition on the estuary bottom to shoreline erosion. The affinity of many key pollutants for

particulates, especially metals and pesticides, and the dynamics of transport and exchange within the estuary, render an understanding of sediments absolutely indispensable to the management of water quality in general. This is compounded by the activity in Galveston Bay of dredging, shoreline alteration, and trawling, as well as the trends in suspended sediments exhibited in recent years. Sediment dynamics should be the focus of a renewed research effort in the bay, ranging from more detailed observation on grain-size spectrum and its effects, to biokinetic processes operating within the sediment itself.

(5) The observed decline in temperature is probably not a serious concern from the water-quality management standpoint, but additional examination of its cause, especially if of climatological origin, may provide additional insight into other processes, such as the decline of chlorophyll-a and the kinetics of dissolved oxygen. We would recommend some modest examination of long-term variability in the climatological controls of the surface heat budget.

(6) The salinity data base assembled in this project is the most comprehensive available for Galveston Bay (and probably any of the Texas bays) and will support analytical studies of salinity response heretofore not possible. It is recommended that salinity variability in Galveston Bay be examined using sophisticated methods of time-series and response analysis to better delineate the rôle of inflow and other hydrographic factors on salinity. This would be valuable, not only because of the intrinsic importance of salinity as a hydrographic and ecological variable, but to yield insight into the time-response behavior of other, less intensely sampled parameters whose concentrations are dominated by internal transports.

(7) The significant observed decline in salinity underscores the gaps in our understanding of even as fundamental (and conservative) a parameter as this. We recommend additional studies of the external controls on salinity. This could probably be most usefully pursued, at least at the outset, by extending the scope of empirical analysis to include the hydrography of the nearshore Gulf of Mexico. As with nutrient and particulate loading, we believe event-scenario and time-series analysis to be most promising. There is also a place for hydrodynamic modeling, but only after the essential controls and responses of the system are much better delineated.